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Two-Tone Test Method for Determining Frequency-Domain Transfer Functions

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A method has been developed and used to nonintrusively interrogate electronic systems to determine their characteristic response to electromagnetic energy. The method involves subjecting the system under test to two continuous wave signal sources of different frequencies, f_h and f_l, and measuring the difference frequency, Δf (that is, $f_h - f_l$), emitted from the system under test. The difference frequency created by the mixing action of nonlinear electronic components within the system is a relative indication of the system's response to f_h, f_l. If the two source signals f_h and f_l are incremented by the same frequency step size, Δf remains constant in frequency and can be measured for each f_h, f_l value. The compilation of amplitude measures of Δf, normalized by the corresponding amplitude measures of f_h, f_l, provides a relative measure of the frequency-domain transfer function of the system under test.

Although the present method provides only relative data, the economic benefits of using this method make it a viable alternative to high-tech, high-cost approaches. The method provides more than coupling data, since the measurement of Δf is indicative of not only the relative coupling efficiency of the signal source (f_h, f_l) into the system, but also the relative response of the nonlinear circuit component(s) that mix the source signals. The present method is performed with the test equipment totally isolated from the system under test. Without the need for probes at circuit nodes, less time and effort are expended and the integrity of the system is not violated by instrumentation.

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1. Introduction

Generally, all electronic systems are required to operate and/or survive in potentially hostile electromagnetic (EM) environments. To harden a system to known or predicted EM environments, one would like to observe the response of the system while it is being subjected to the EM environments of concern, make design changes to mitigate undesirable responses, and finally test the redesigned system to verify the effectiveness of the redesign. Because potential EM threats are extremely numerous, it can be difficult and expensive to reproduce them and subsequently test the system to all environments of concern. Furthermore, any given system will be inherently hard to some EM environments and soft to others; therefore, it is economically prudent to test the system only to those environments that could actually pose a threat to the system.

Various methods have been devised and practiced to obtain data that describe the behavior of a system subjected to external EM environments. Many of these techniques are targeted at obtaining the frequency-domain transfer function of the system. Once the frequency-domain transfer function is known, the transfer function may be numerically convolved with any source environment to produce the system response (linear) to that source. In this way, any number of EM environments may be convolved with the system transfer function inexpensively and quickly via computer so that one can assess which EM environments might cause an undesirable response in the system. Further testing and design changes may then be focussed on the smaller number of EM environments that are identified as potentially threatening.

To understand how the EM environment is coupling to, entering into, and affecting the system, we need the data collected (transfer functions) to be in the form of normalized electrical responses (voltage or current) at one or more circuit nodes. To obtain these measured voltages and currents at circuit nodes, a probe must be inserted near the circuit node. The insertion of the probe and the probe itself can corrupt the collected data by loading the circuit node and modifying the system's topology and hence transfer function. An ideal method of obtaining the transfer function would be to use an instrumentation system that is physically isolated from the system under test (SUT) so that the measurement system does not influence the system or the incident EM environment. Furthermore, for testing the system to all EM environments of concern, wide-band probes and sensors are usually required to cover several decades of frequency.

The present novel method for determining the frequency-domain transfer functions of an electronic system is a noninvasive technique that is performed totally external to the system under investigation. The methodology involves subjecting a system to two EM signals of different fundamental frequencies, f_l and f_h (tones), and measuring an EM signal leaving the SUT whose characteristic frequency is the arithmetic difference of frequencies f_l and f_h ($f_h - f_l = \Delta f$). This difference frequency, Δf, occurs because of the mixing of f_l and f_h by nonlinear electronic components within the SUT. The mixing action also produces a sum frequency $f_h + f_l$ and harmonics of the sum and difference frequencies, but the difference frequency is the component sought, because it remains constant in frequency as long as f_l and f_h are incremented by the same amount over the frequency range of interest.

It must be emphasized that this method is not intended to replace the commonly used methods incorporating internal probes and wide-band instrumentation. The present method does not provide more accurate results or necessarily better results; it is used simply to screen a test object so that general information can be obtained regarding the system's EM response. The method was specifically developed to enable a test engineer to quickly screen a test object when coupling studies would otherwise not be performed because of rigid time and financial restrictions. Before testing a system to full-scale EM sources (EM pulse, EM interference, high-power microwaves, etc), the engineer can use the two-tone method to determine candidate frequencies for testing. The two-tone method in its simplest form gives the test engineer a starting point. The two-tone method suggests areas of concentration within the EM spectrum, which may save time and money compared to hit-and-miss "bang" testing.

2. Background

To date much has been invested in developing probes and sensors that are very small, have very wide response bandwidths, and are made out of nonmetallic parts (photonics). Small size is required for the probes to be "implanted" in small systems and in general is desired to minimize the impact on the system's topology. The wide-band requirement is sought as a time- and money-saving feature because it allows more data to be collected per test shot. The push for photonic sensors is based on the fact that metallic sensors can affect the topology of the system or adversely alter the EM environment. The development of high-tech sensors has proven to be very expensive and is often plagued with the problems associated with pushing the edge of technology.

The instrumented approach to obtaining frequency-domain transfer functions is often costly and time consuming. Instrumenting the SUT can damage the test object or corrupt test data. Much of the allotted resources for a particular test object can be expended in obtaining transfer function data, whereas these resources might be better applied to the "full-scale" response tests. Another problem occurs when a test object is borrowed. Borrowed assets must usually be returned in a relatively short period of time and must be returned undamaged and unmodified. These factors led to the development of the present method.

The present method offers an alternative to the high-dollar, high-technology approaches. Although the present method provides only relative data, the data are obtained quickly and inexpensively and, more importantly, without data corruption or damage to the SUT.

3. General Discussion of Method

In this method, a test object is simultaneously subjected to two signal sources of different fundamental frequencies (f_{l_1} and f_{h_1}); one then measures the amplitude of the signal leaving the test object at a frequency Δf_1, which is the arithmetic difference of the two source frequencies ($f_{h_1} - f_{l_1}$). This difference frequency is indicative of the two source signals entering the test system, reaching at least one nonlinear electronic component, and mixing. The above procedure is then repeated with new source frequencies f_{l_2} and f_{h_2}, whose difference frequency Δf_2 is equal to Δf_1, and the same difference frequency is monitored emanating from the system. This procedure is continued for all frequencies of interest, f_{h_n}, f_{l_n}.

Each amplitude measurement of Δf_n is normalized by the amplitude of f_{l_n} and f_{h_n}, and the cumulation of these normalized data in total represents the relative response of the system's electronic circuitry to external EM stimulation over the frequency range from f_{l_1} to f_{h_n}. The normalized data (Δf normalized by f_l, f_h) do not represent an absolute quantification of the system but simply represent the relative response of the system over the frequencies of interest. If the normalized data for Δf_1 are a factor of 10 greater in amplitude than the normalized data for Δf_1, for example, this simply indicates that the system in general is 10 times more responsive to frequencies in the range of f_{l_1}, f_{h_1} than to frequencies in the range of $f_{l_{14}}, f_{h_{14}}$.

The SUT will obviously have a different transfer function for each orientation, EM field polarization, operational configuration, etc. Therefore a complete characterization of the system may actually in-

volve many transfer functions, or a worst-case transfer function, or a statistical spread of the measured transfer functions. Although several different equipment configurations and test setups may be used to obtain the desired data, all obey the basic methodology. The type of SUT and the type of data sought will determine the appropriate test configuration. All test configurations are easily adapted to computer control for efficient operation and analysis of the resultant data.

4. Detailed Description of Method

Figure 1 depicts the equipment layout for the single-antenna free-field technique of measuring the transfer functions of an electronic system. Two signal sources are used to generate two sinusoidal signals of frequency f_l and f_h, respectively. The two sources may be sine-wave generators, network analyzers, or any other signal source capable of producing ac signals over the frequency range of interest. The sources are represented in the figure by two network analyzers, NA 1 and NA 2. The two signals f_l and f_h are combined by a signal combiner, and the combined signal is fed to a signal amplifier. The combined signal is amplified and fed through a high-pass filter to a radiating antenna. The combined and filtered source signal is radiated toward the SUT. The source signal will couple to the SUT, enter the SUT, travel circuit pathways, and eventually reach nonlinear electronic components. The nonlinear components will mix the f_l

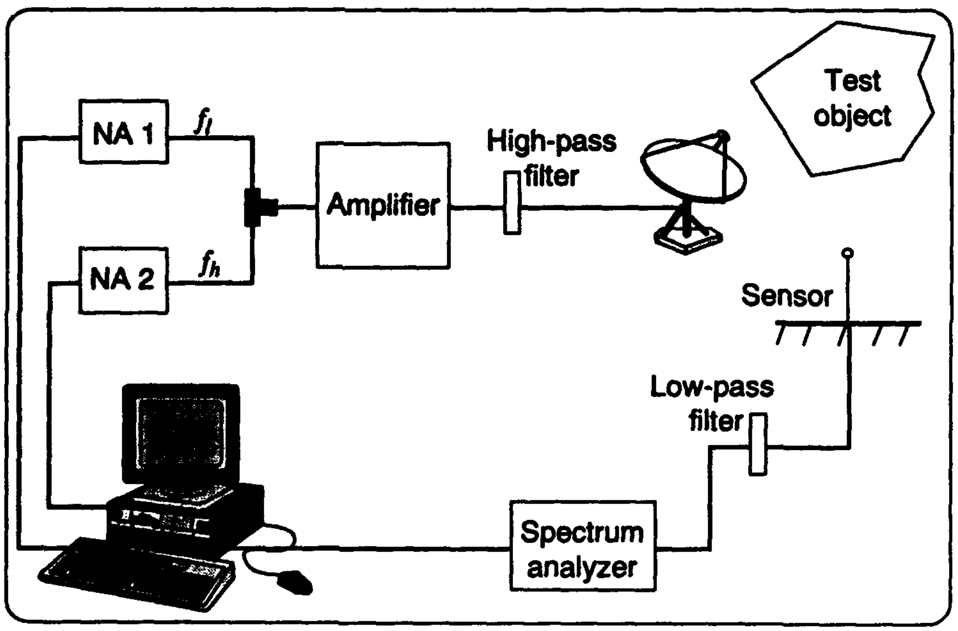


Figure 1. Free-field method with single antenna.

and f_h fundamental components in the source signal and produce the difference frequency Δf ($f_h - f_l$). The Δf signal will travel pathways and radiate from the SUT. The remotely located sensor detects the Δf signal radiating from the SUT and feeds the detected Δf through a low-pass filter to a measuring device such as a spectrum analyzer. An optional computer controller may be used to control the signal sources and retrieve and archive data from the measuring device.

The mixing action that occurs at the nonlinear electronic components actually produces sum ($f_h + f_l$) and difference ($f_h - f_l$) frequency components, as well as harmonics thereof. Since the harmonics will be severely reduced in amplitude, they are not chosen as the signal component to be measured. One could attempt to measure the sum component ($f_h + f_l$); however, as f_h and f_l are incrementally changed in testing the SUT over all frequencies of interest, the sum component will change in frequency and continue to increase. To measure the sum signal, one would need a wide-band high-frequency measurement system; however, using wide-band equipment would lose the advantage of the present method, which involves only narrow-band measurements. Additionally, since the sum signal would change with each incremental change of f_h and f_l, the reverse transfer function of the sum frequency from within the SUT to the sensor would also change with each incremental change and therefore would have to be known for the measured data to be corrected. Therefore, the difference component $f_h - f_l = \Delta f$ is chosen as the signal to be measured. When f_h and f_l are incremented by the same amount, the Δf component remains constant in frequency. With Δf constant, a tuned narrow-band sensor can be used. And although the transfer function of Δf from within the SUT to the sensor is unknown, it is constant for all incremental values of f_h and f_l. Since the data are relative and not absolute, the unknown transfer function of Δf from the SUT to the sensor is inconsequential because it is a constant.

The Δf signal radiating from the SUT indicates not only the coupling efficiency of the source signals into the SUT, but also the mixing efficiency (component response) of the nonlinear components that produced the Δf signal. The amplitude of Δf depends on the amplitude of f_h and f_l components that reach the nonlinear electronics and is therefore indicative of the coupling efficiency of f_h, f_l into the SUT. The amplitude of Δf also depends on the efficiency of the nonlinear components in mixing f_h and f_l and is therefore indicative of the electronics' response to frequencies f_h and f_l. Because the SUT coupling efficiency, the electronic component response, and the coupling effi-

ciency of Δf from inside the SUT to the sensor are inseparably combined in the measurement of Δf at the sensor, the data as collected are relative and not absolute.

4.1 Δf Considerations

Before one chooses the appropriate equipment for the system(s) to be tested, a few design choices and unknowns must be resolved. First, one must decide what frequency range will be covered and choose the sources to accommodate this range of frequencies. Second, one must determine how wide (in frequency) the resonant response bandwidths of the SUT are or are expected to be. Although a system will have peak responses at certain frequencies, these response peaks do not have zero bandwidth; rather, there is some range of frequency variance both above and below the resonant peak to which the system will respond with reasonable power variances (3 dB). Once the 3-dB resonant response bandwidth is determined, Δf must be chosen so that it is smaller than the 3-dB resonant response bandwidth of the SUT. Because f_h and f_l are not the same frequency, they will each couple into the SUT differently. If one chooses the difference between f_h and f_l (Δf) to be small compared to the resonant response bandwidth, the variance in coupling efficiency of f_h versus f_l will be small or negligible or at least bounded. Also the values of f_h and f_l should never equal Δf. In choosing Δf, one must also consider the reverse transfer function of Δf from within the SUT to without. It is desirable, for signal-to-noise (S/N) considerations, that the Δf component be capable of radiating out of the system with as little power loss as possible. The approach to choosing Δf is simply that Δf should be made as small as possible so that (1) the instrumentation used can adequately discriminate f_h and f_l and (2) Δf can radiate out of the system with minimal power loss. All effort should be made to keep Δf much smaller than the resonant response bandwidth.

4.2 High-Pass Filter Design

Some of the signal f_l from source 1 will leak into the output port of source 2, and likewise some f_h signal will leak into source 1. Since the sources contain circuitry with nonlinear electronic components, each source will mix the two signals and produce signals of frequency Δf ($f_h - f_l$). The amplifier will amplify the Δf created by sources 1 and 2, and since the amplifier also has nonlinear electronic components, the amplifier will also mix fundamentals f_l and f_h and produce amplified Δf signals. Because the test equipment is mixing the source signals and producing Δf signals, these Δf signals must be filtered

out before the signals are radiated at the SUT via the antenna. If the Δf created by the test equipment were not filtered out, this artificial Δf would be radiated and hence measured by the sensor and would be indistinguishable from the Δf signals actually created by the SUT, thereby corrupting the data. The only Δf desired is the Δf component created by f_l and f_h mixing within the SUT. The filter is preferably passive and should be high-order, providing 80 dB or more attenuation in the stop band and minimal attenuation and phase distortion in the pass band. Additionally, caution must be used if the filter is to be active, since active filters may themselves cause mixing and incidental Δf signals. The filter must be chosen so that Δf lies well within the stop band and the lowest value of f_l is well within the pass band. The filter must also have a power rating appropriate for the amplifier to which it is connected.

4.3 Measurement System

The sensor should be tuned at the chosen Δf to minimize S/N problems. Since Δf is constant, the sensor can be easily constructed to optimize the narrow-band measurement of Δf. The sensor is preferably passive so that it does not create extraneous Δf signals by mixing incidental f_h and f_l that it may pick up. The measuring device can be any receiver capable of being tuned narrow-band to Δf, such as an rf receiver, spectrum analyzer, power meter, etc. Because the measuring device may contain nonlinear electronic components, incidental f_h and f_l signals picked up by the sensor must be filtered out so that they are not mixed in the measuring device to produce extraneous Δf signals. The low-pass filter should be of a high-order design so that Δf is well within the pass band and all values of f_h and f_l are well within the stop band.

4.4 Data Processing

For obtaining the frequency-domain relative transfer function of the SUT, the signal source 1 is originally set to f_{l_1}, which is the lowest frequency of concern for the transfer function, and source 2 is set to f_{h_1} (that is, $f_{l_1} + \Delta f$). The SUT is subjected to these signals and Δf_1 is measured via the sensor and measuring device. The measurement of Δf_1 is then sent to a computer for processing and storage. Then source 1 is incremented to produce signal f_{l_2} and source 2 to f_{h_2} (that is, $f_{l_2} + \Delta f$), and Δf_2 is measured. This procedure is repeated until the highest frequency of concern for the transfer function, f_{h_n} (that is, $f_{l_n} + \Delta f$), is reached. The amount to increment the source signals is chosen based on the resolution desired and the responsiveness of the

SUT to the frequency range of concern; the only requirement is that sources 1 and 2 be incremented by the same amount.

The measured and stored amplitude values of Δf must be normalized by the corresponding source signal incident on the SUT. Because the sources, the amplifier, and the antenna will exhibit frequency-dependent behavior, the measurement of each Δf_n must be normalized to account for variances in corresponding f_{h_n} and f_{l_n} incident on the SUT. Since the data are only relative, there is no requirement to normalize the data by an absolute measure of f_h and f_l; therefore, the data can be normalized in several ways as long as all data are treated consistently. One method would be to normalize the measurement of each Δf by the product of the corresponding f_h and f_l,

$$\frac{\Delta f_n}{f_{h_n} f_{l_n}},$$

for each value of n.

Alternatively, Δf could be normalized by the average amplitude of f_h and f_l,

$$\frac{\Delta f_n}{\left(\frac{f_{h_n} + f_{l_n}}{2}\right)},$$

for each value of n. Other equally valid normalization procedures may be used as long as all data are treated consistently and the normalization accounts for amplitude variances of incident f_h and f_l for each data point. The values for f_h and f_l to be used in the equations given above must be amplitude values for the signal incident on the SUT. The amplitude values of f_h and f_l may be obtained through measurement of the f_h and f_l signals at the SUT or numerical extrapolations of the signal source settings, or a combination of both numerical and empirical measures. The normalized values of Δf (Δf_l ... Δf_n) represent a relative frequency-domain transfer function for the SUT.

5. Description of Alternative Setups

Figure 2 is a variation of the equipment setup shown in figure 1. Here the two sources 1 and 2 are separately fed to amplifiers, filters, and antennas, and are not combined as in figure 1. Because the source signals are not combined, there is less of an opportunity for the signals to mix and produce Δf in the source equipment. There is

still the possibility (based on proximity and orientation) that signals emitting from one antenna could couple to the other antenna, reach an amplifier, and mix. This cross coupling can usually be minimized by proper placement of the antennas. Filters (indicated in the figure by dashed boxes) may be used for added precaution; however, the performance characteristics of the filters may be more relaxed than in the method of figure 1.

Figure 3 is a variation of figure 1 in which the source signals are not radiated at the test object but rather are directly injected onto the test object. Here the test object is made part of a coaxial test fixture (transmission line). With the test object used as the center conductor,

Figure 2. Free-field method with two antennas.

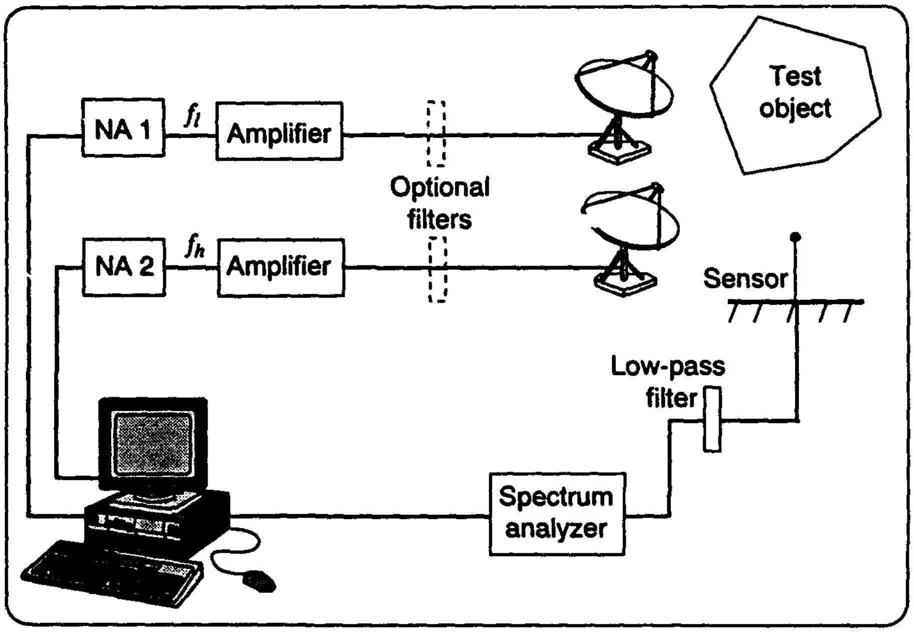
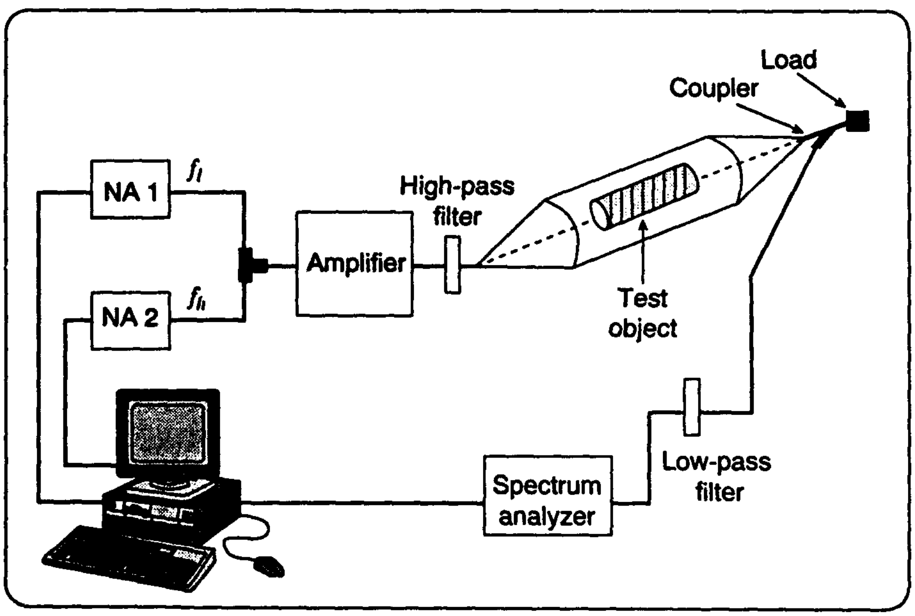


Figure 3. Transmission-line (direct inject) method.



an outer coaxial conductor (shield) is formed, completely enclosing the test object. The measurement of Δf may be obtained and fed to the filter and measurement device by a sensor or probe within the transmission-line structure. Alternatively, one could place a directional coupler before the load (as shown in fig. 3) and feed a signal to the filter and spectrum analyzer. A directional coupler is needed in this direct-connect method; otherwise, the low-pass filter would present a low impedance to the transmission line. The impedance mismatch created by the filter would cause standing waves and therefore could corrupt the results. The advantage to this setup versus that of figure 1 is that of high source signal strength. With the test setup of figure 3, less source signal power is lost than when the source signals are radiated. With more source signal power delivered to the test object, Δf will have a larger power and therefore be easier to measure since S/N requirements of the measurement system will be relaxed. A disadvantage is that it may be difficult or impossible to perform parametric studies of field polarization, orientation, and configuration because of physical limitations of the direct-inject technique.

Figure 4 is a variation of the setups in figures 1 and 3 in which an attempt is made to exploit the advantages of each. Here the test object is illuminated by bounded transverse electromagnetic (TEM) fields. By bounding the TEM in a TEM cell, one can apply high EM power to the SUT, and by using an adequately sized cell, one can perform orientation and configuration studies. Here the structure must be loaded with a dummy impedance. The measurement sensor may be placed within the cell to measure radiated Δf.

Figure 4. TEM cell method.

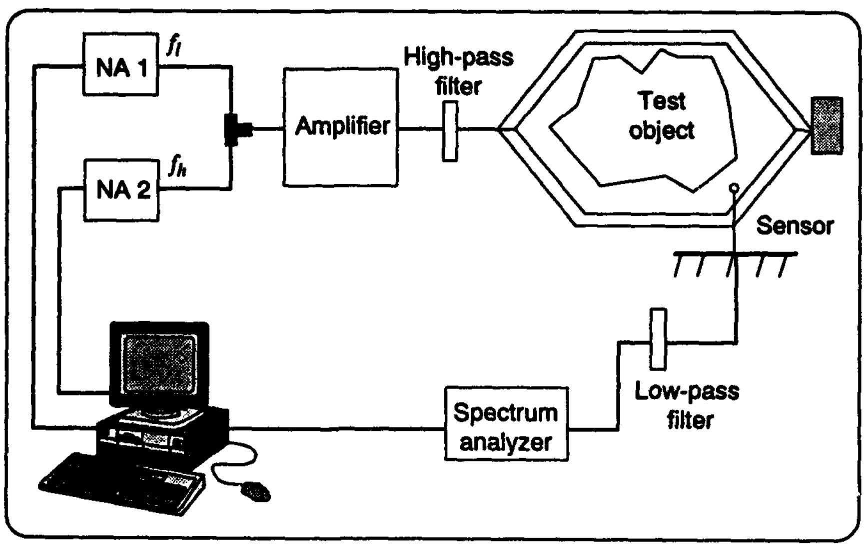
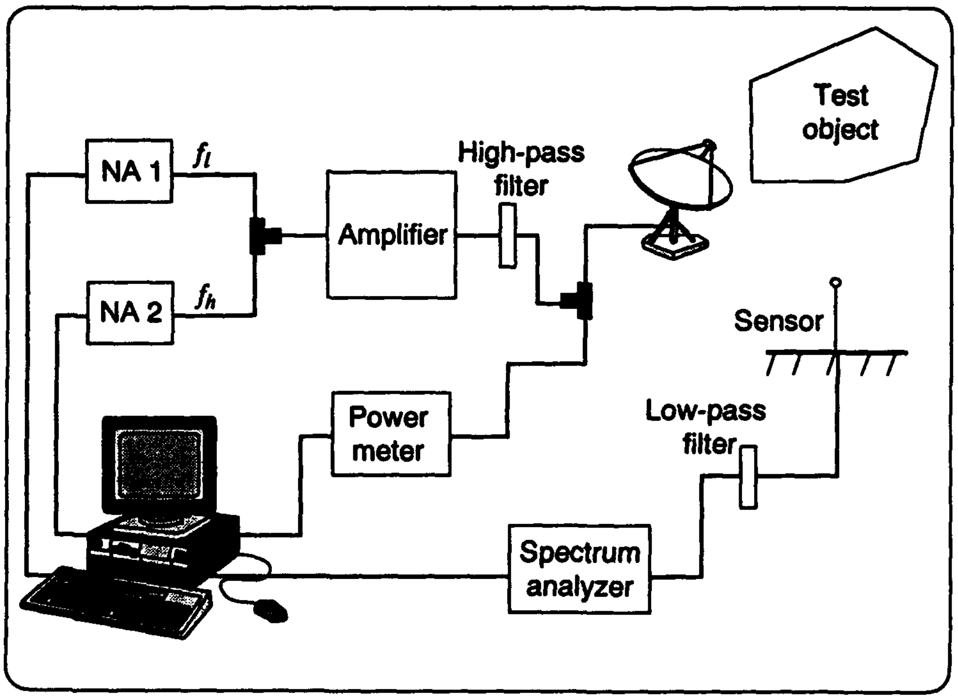


Figure 5 is shown as a variation of the setup in figure 1; however, the modifications may be applied to any of the setup variations in figures 1 to 4. As discussed above, a computer may be used to collect and process data, as well as to control the signal sources and other instrumentation. Here a signal splitter is used to pick off a portion of the source signal, and a second measuring device (shown in the figure as a power meter) is used to provide feedback to the computer controller. In this manner an automatic gain control (AGC) has been established, and the computer may be used to measure the amplitude of f_h and f_l being produced and subsequently adjust the signal sources 1 and 2 so that f_h and f_l are equal in amplitude and constant over the frequencies of interest. By keeping the composite source signal amplitude constant, one can eliminate the normalization of the measured Δf or at least make it rather trivial. The location to pick off and feed back the source signal depends on the frequency response of the equipment used. The pickoff point shown in figure 5 is appropriate for an antenna that is flat in frequency response for frequencies of interest. However, if the antenna frequency response has significant structure over the frequency band, the pickoff point may necessarily be located some distance in front of the antenna and comprise a sensor and a measuring device, as illustrated in figure 6. If the antenna response has been measured and digitized, the pickoff could be as shown in figure 5, the measured feedback could be numerically corrected by the computer for antenna response, and the appropriate adjustments made and sent to the signal sources. This setup is extremely useful in automating the test procedure.

Figure 5. AGC direct measure adaptation.



6. Results

Figure 7 is a representative waveform for a tested system, obtained from voltage probes. The waveform shown is actually a normalized average of three circuit node test points obtained with various system configurations; the waveform has been normalized to its maximum amplitude. The original data from which figure 7 was obtained were absolute transfer function data in the form of coupling cross sections (in cm^2). I obtained the original data by inserting and attaching voltage probes to the circuitry within the test object, illuminating the object with EM fields in an anechoic test chamber,

Figure 6. AGC remote sensor adaptation.

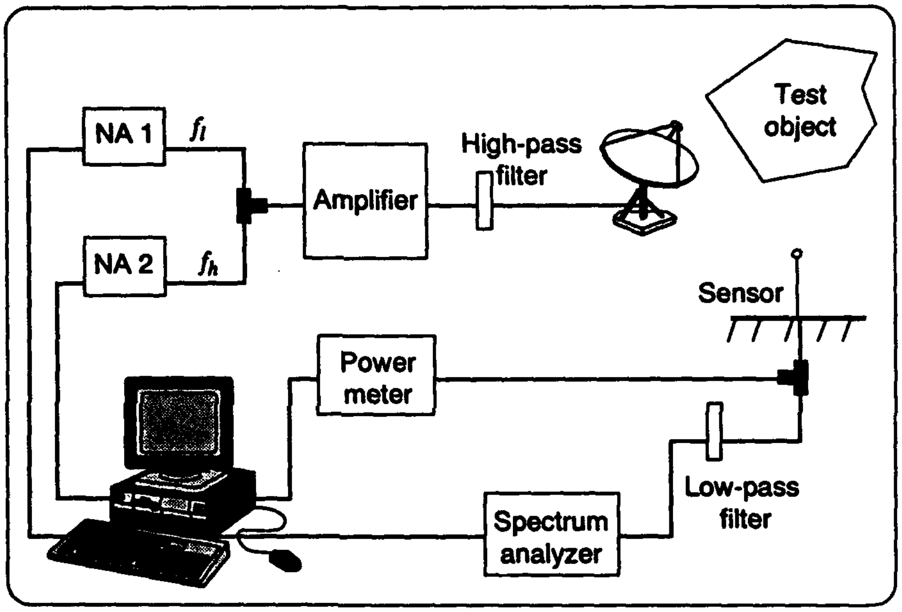
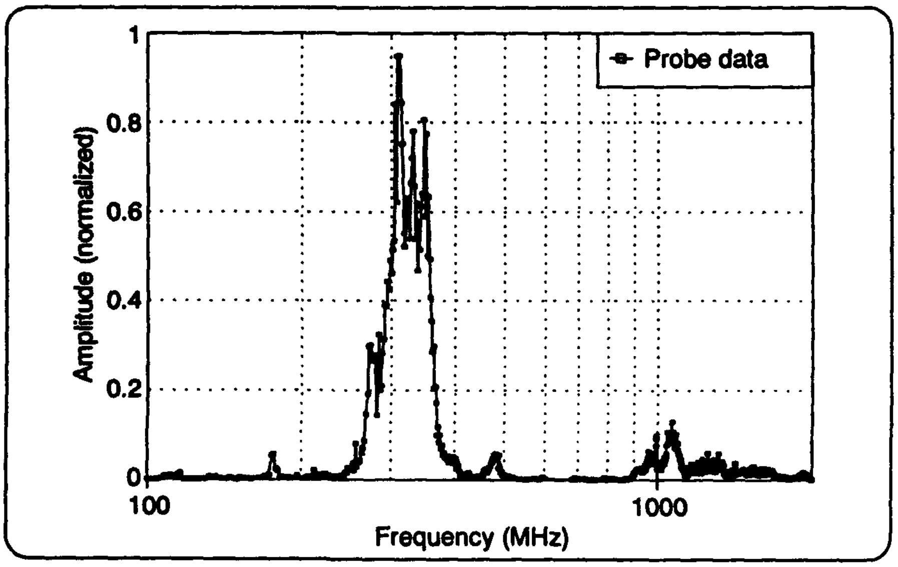


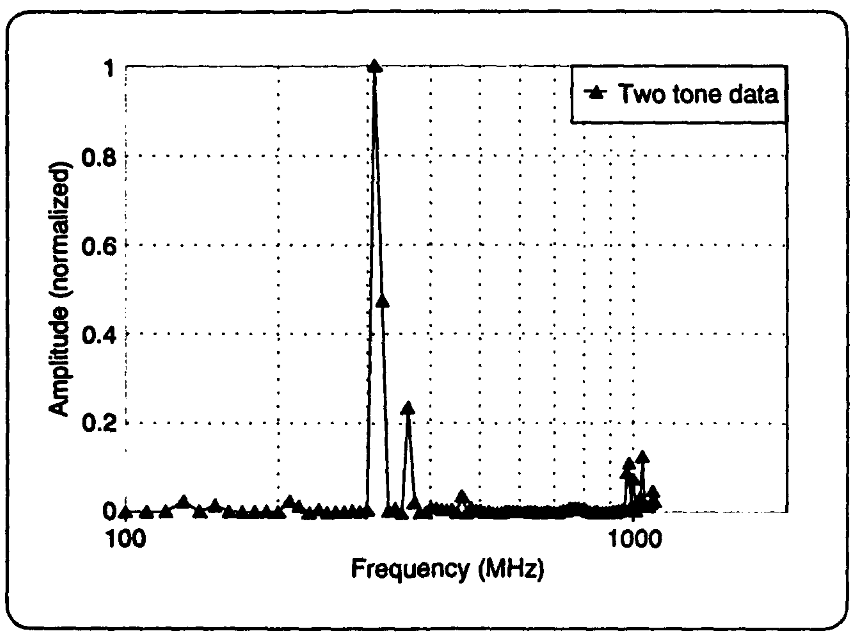
Figure 7. Averaged and normalized probe test data.



measuring the voltage at the test points, and normalizing the measured voltage data by the incident EM fields. The waveform in figure 7 (as well as most of the data taken) shows the system to have main structure at approximately 300 MHz, 310 MHz, and 1 GHz.

Figure 8 is the result obtained with the two-tone method applied to the same system as was used for the data in figure 7. Here the data were taken with the setup of figure 3, and thus represent the response of the system as a whole. The waveform in figure 8 has been normalized to its maximum amplitude independent of the waveform in figure 7. The data taken with the present meth[illegible] match very well with those of figure 7. Because the two-tone dat[illegible] obtained with the direct-inject technique and therefore represe[illegible] response of the SUT as a whole, the waveform of figure 7 was necessarily composed of a number of different test points and configuration variations so that a whole system response could be approximated, thereby facilitating a comparison of the two waveforms. Although the present method provides only relative data, the important feature of the data is that like figure 7, figure 8 shows primary structure at approximately 300 MHz, 310 MHz, and 1 GHz. Figures 8 and 7 are also consistent in relative amplitude; for example, figure 8 shows the 300-MHz resonance to be about 8 to 10 times the amplitude of the resonance at 1 GHz, which is independently indicated in figure 7.

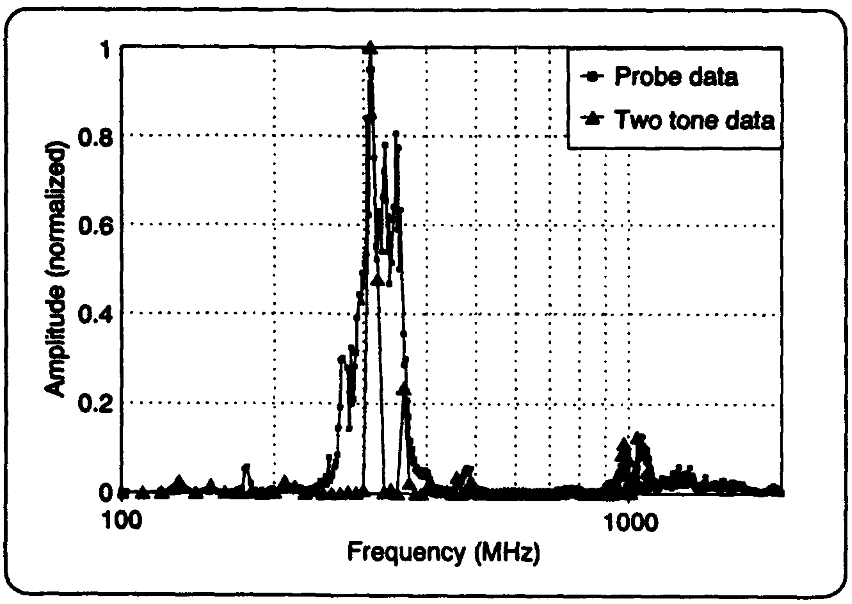
Figure 8. Two-tone (direct inject) results.



Perhaps of equal importance is that the test efforts involved in obtaining the data shown in figure 7 represent approximately 3 man-months' worth of effort (a conservative estimate), whereas the data of figure 8 using the present method (not automated) represent approximately 3 man-hours' worth of effort (a liberal estimate). The probe method of obtaining data requires circuit analysis and exploitation of the SUT for the selection of the test points. Next, probes must be designed, fabricated, and installed in the system. Then the system must be tested at an EM test facility, such as an anechoic chamber, which often requires several personnel and a large amount of diagnostic equipment and instrumentation. This process can be very time consuming and expensive (in personnel and test facility costs). The estimate of 3 man-months can increase many times for large complex systems. In contrast, the two-tone test data shown in figure 8, although sparse, required one operator and were collected in approximately 3 hours including processing time (not including the R&D for this technique).

Figure 9 is an overlay of figures 7 and 8, comparing the two methods. Each waveform was independently normalized to its own maximum value. Although the two-tone data are sparse and contain less structure than the probe data (which may be a result of the data sparsity), all major resonances are indicated and are in proper proportion. Recall, also, that the two waveforms were not obtained for identical test points or configurations, and the two-tone data have embedded nonlinear component responses that are not evident in standard probed transfer functions. The two-tone data were collected manually, and in this experimental test series, some S/N

Figure 9. Comparison of two-tone results and probe data.



problems were encountered that may explain the differing structure. Because most of the Δf measures were made near the noise floor, only the peaks were easily distinguished as data. With higher source power, or perhaps statistical data processing, the two-tone method will show more structure.

7. Summary

A method has been developed to determine a system's response in the frequency domain. The method uses two EM source frequency tones to interrogate the SUT and a measurement system to detect a response frequency emitted from the SUT. The emitted frequency signal, Δf, is equal to the arithmetic difference of the source signal frequencies and is created by the mixing action of nonlinear electronics components within the SUT. The amplitude of the measured Δf signal relative to the amplitudes of the sources' signals is indicative of the coupling efficiency of the source signals into the system and the mixing efficiency (response) of the electronics within the SUT.

The present method can provide relative frequency-domain transfer functions for a system quickly and cost effectively. The method requires only standard off-the-shelf test/diagnostic equipment. Since the method can be employed totally external to the SUT, it does not damage the SUT, does not affect the SUT's topology, and does not corrupt the test data. The technique provides less than a standard absolute transfer function in that the resultant data are relative only, and provides more than a standard transfer function in that the method inherently provides response functions of the nonlinear components within the system.

Although an absolute comparison of the two-tone results to standard test method results is not possible because of the differences in the content of the resultant data, a comparison should be possible regarding general system characteristics and responses. A comparison of the two-tone data to probed transfer function data indeed does indicate that both techniques provide data indicating major system resonances. Furthermore, the comparison shows agreement between the two methods in their indication of the relative amplitudes of the resonances. The two-tone test method has been shown to be a valuable tool for determining the frequency-domain response characteristics of electronic systems.

8. Conclusions

The two-tone test method has the advantages and limitations given in table 1. As the table shows, the method is quite limited by comparison to wide-band probed methods. However, because the method requires so little time, money, and preparation, it can be an extremely valuable tool for determining frequency responses of systems.

The two-tone method may require high S/N measurement capability for detection of the Δf signal (or high source power requirements). Likewise, the high-pass and low-pass filters may require strict design specifications. The two-tone method provides only relative data, which may pose problems where portability of data is a concern. It may not be possible to directly compare two-tone data that have been obtained under different conditions or configurations. Relative data require special care and bookkeeping for configurational or equipment changes. It may not be possible to normalize two-tone data to absolute data; therefore, setup and condition qualifiers must accompany all data. Additionally, the two-tone data represent an average response of the system, in that the Δf measured may be a composite signal created by more than one component, circuit, or subsystem within the SUT.

The two-tone test method is a valuable tool for hardening studies. After obtaining the "baseline response" of the unmodified SUT, one

Table 1. Advantages and limitations of two-tone method.

Advantages	Limitations
Faster than probing SUT's	Data obtained are relative, not absolute
Cost-effective	Data indicate average response of system only
Provides component response (nonlinear)	Strict S/N requirement—method requires measurement of small signals
Requires only simple sensors (no wide-band)	Strict filter requirements—method requires good filtering
Noninvasive to the SUT (no internal probing)	Because data are relative, it may require extra effort to maintain relatability to other data
External—all sources and instrumentation are external to the SUT	
Standard instrumentation, no wide-band	

could proceed to add hardening measures and quickly retest the SUT to evaluate the effectiveness of such measures. In the past, some hardening measures and evaluations have focused on preventing the incursion of the incident EM energy. Because the present method provides component response data, the hardening measures that could be evaluated are not restricted to those stopping the entrance of EM energy, but may also include efforts to block the EM signals from reaching specific circuits or components. That is, the present method enables efficient evaluation of site-specific hardening measures and is not limited to evaluating whole-system shielding measures.

Because the limitations of the two-tone method leave the engineer with a limited understanding of the system's response to EM energy, data obtained by the present method are less useful than probed absolute transfer function data, which can provide a better understanding of the system. However, the two-tone method also brings numerous advantages. The two-tone method is fast and cost effective, and it can be performed with standard instrumentation. Furthermore, the two-tone method is performed external to the SUT and does not corrupt the data or EM environment. There are instances when probed testing must be foregone altogether because of time, cost, or equipment constraints. In many instances, these constraints can be overcome with the two-tone method.

The two-tone method can provide data that indicate how a system will generally respond to EM energy. It can provide the resonances of a system (the "sweet spots") and the relative strength of the resonances to one another. Because the two-tone method provides electronic component (nonlinear) response, the data provided are extremely useful when the actual source of concern has a modulated composition. The mixing phenomenon upon which the present method relies is directly indicative of the system's ability to demodulate a carrier signal (rectification efficiency). By its very nature, the present method perhaps can be most beneficial as a screening tool to determine frequency sweet spots and/or the rectification efficiency of a system before the SUT is subjected to full-scale testing, such as EM pulse, EM interference, EM compatibility, high-power microwaves, electronic countermeasures, etc.

9. Future Efforts

Future investigations on the following topics are desirable for determining the full breadth of applicability and further enhancing the performance of the two-tone test method:

1. Automate the method under computer control.
2. Examine various AGC feedback configurations to complement automation.
3. Evaluate method in mode-stirred anechoic chamber.
4. Perform tests on wider varieties and types of systems.
5. Examine digital signal processing techniques to enhance signal-to-noise ratio.

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